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Design and Development of Aerogel Based Antennas for Aerospace Applications

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NASA Aeronautics Research Mission Directorate (ARMD)

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Outline

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- Background
- The innovation
- Technical approach
- Results of the Seedling effort to date
- Distribution/Dissemination
- Next steps



Objective and Payoff

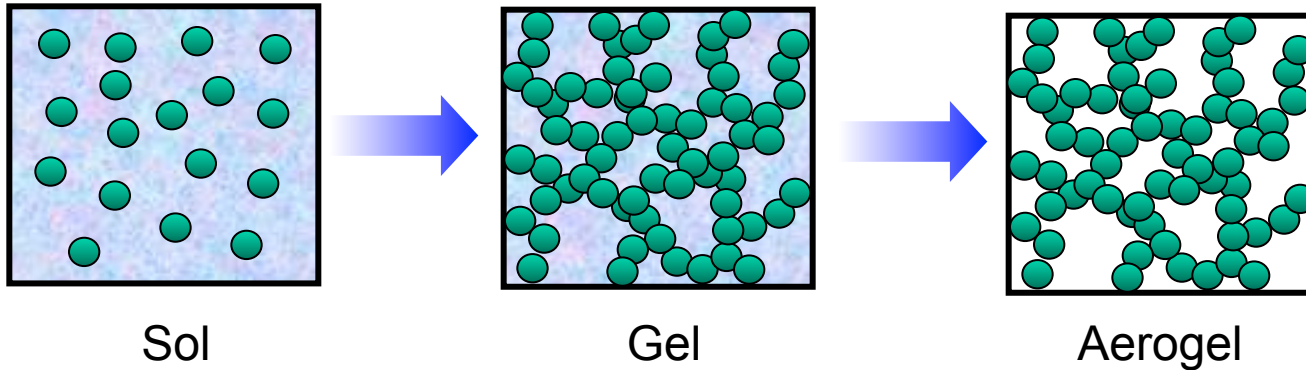
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- Objective
 - Evaluate potential for using aerogels as a substrate for antennas
- Impact of the innovation if it is eventually implemented
 - Increased bandwidth and gain over state of practice antenna substrates
 - Reduced antenna weight

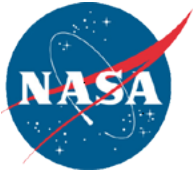


What are aerogels?

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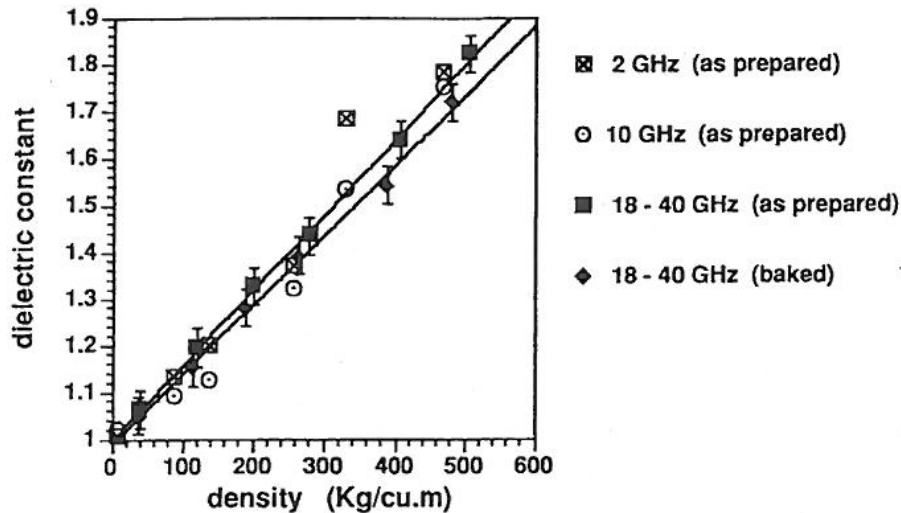


- Highly porous solids made by drying a wet gel without shrinking
- First fabricated in 1930s by Prof. Samuel Kistler
- Pore sizes extremely small (typically 10-40 nm)—very good insulation
- High surface areas
- Density as low as 0.008 g/cm^3
- Low density = low dielectric constant and loss

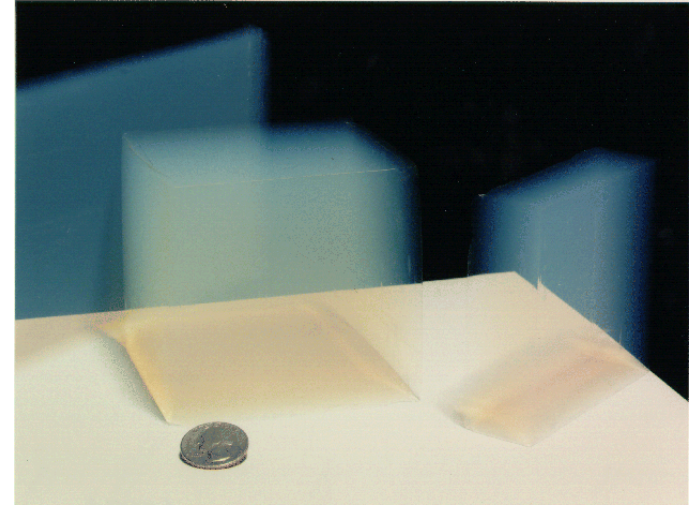


Silica aerogels most well studied

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Dielectric constants of aerogels graphed as a function of density



Typical monolithic silica aerogels

- Dielectric properties vary linearly with density
- Lowest dielectric constant reported: 1.008 for silica aerogel with density of 0.008 g/cm^3
- Hrubesh, Keene and Latorre, *Journal of Materials Research*, **1995**, 8, 1736-1741



The innovation

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- Previously studied silica aerogels
 - Many amazing properties, including low relative dielectric constant, low density
 - However, very fragile
- Recently developed polyimide aerogels
 - Same low density
 - Mechanically robust
- Take advantage of the superior mechanical properties, light weight, low dielectric properties of polyimide aerogels to use as antenna substrate



Silica aerogel



Polyimide aerogel

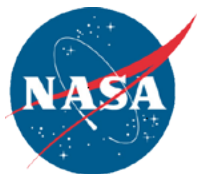


Technical Approach

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Phase I

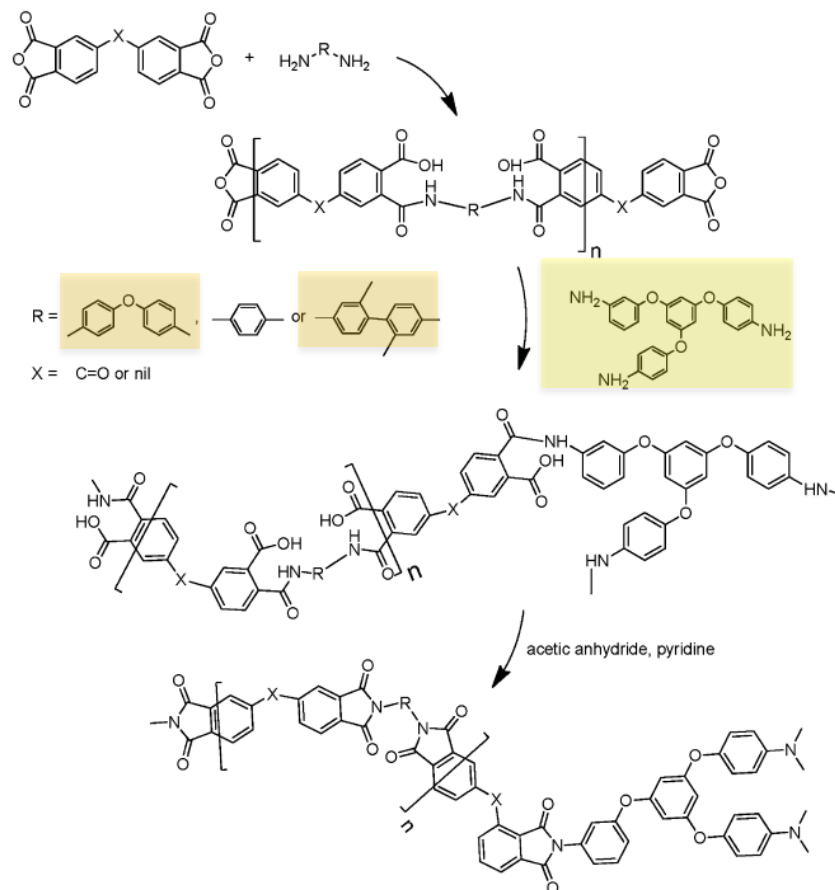
- Fabricate series of polyimide aerogel formulations
- Characterize complex permittivity, other relevant properties for antennas
- Downselect PI aerogel formulation and build prototype single element and microstrip phased array antennas
- Benchmark against state of practice Duroid substrates



Polyimide aerogels

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- Family of aerogels
- More than twenty different kinds of backbone chemistry have been examined
- Two different cross-linkers
- Phase I focused on triamine cross-linker, two diamines and two dianhydrides



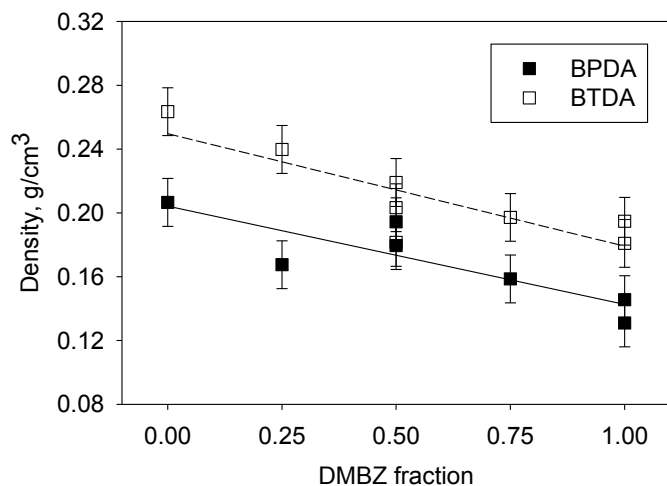
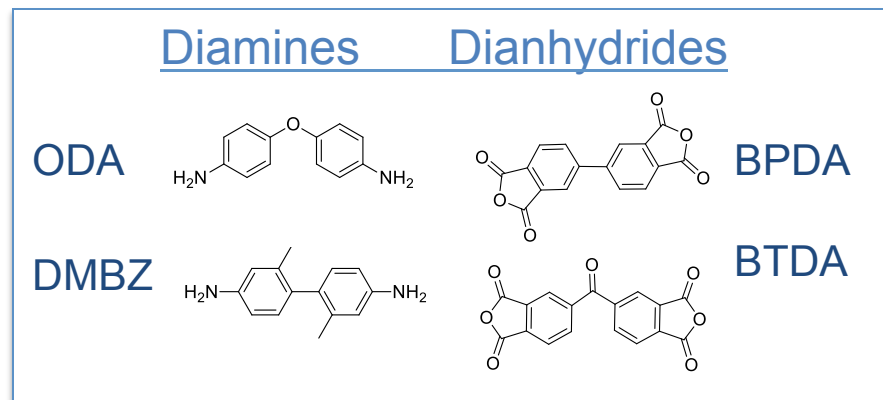
Meador, US Patent application filed 9-30-2009
Meador and Guo, US Patent application filed 2/4/2012



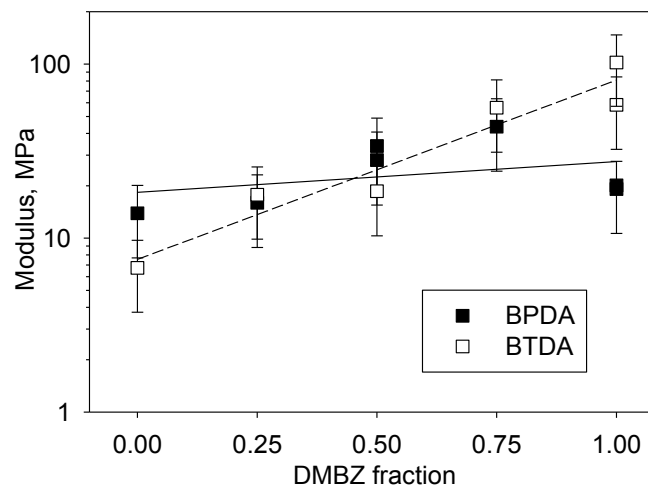
Properties of PI aerogels vary based on backbone chemistry

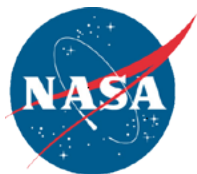
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- Density decreases with increasing amount of DMBZ
- BPDA gives lower density aerogels than BTDA
- Compressive modulus increases with increasing DMBZ



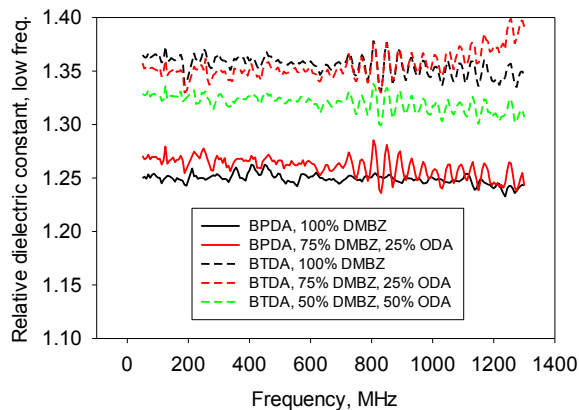
DMBZ fraction is that of total diamine (ODA + DMBZ)



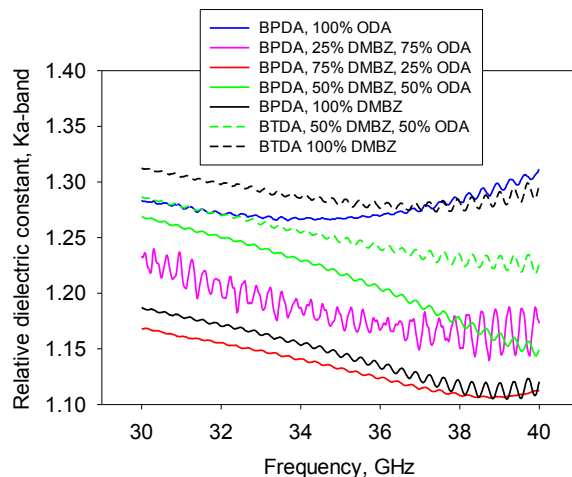


Dielectric measurements at different frequencies

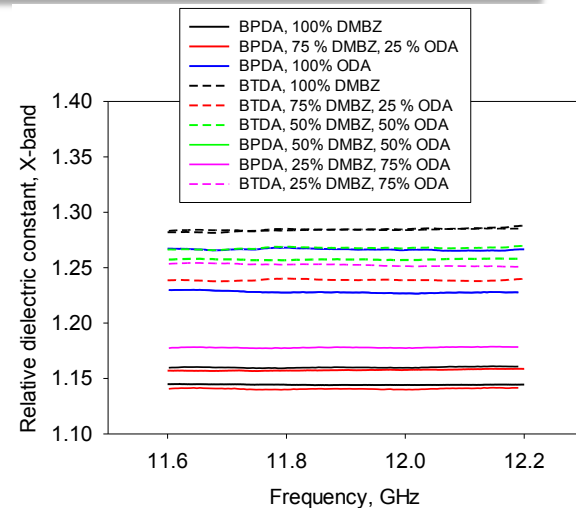
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Low frequency

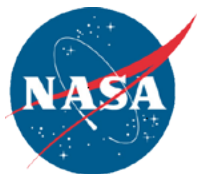


Ka-band



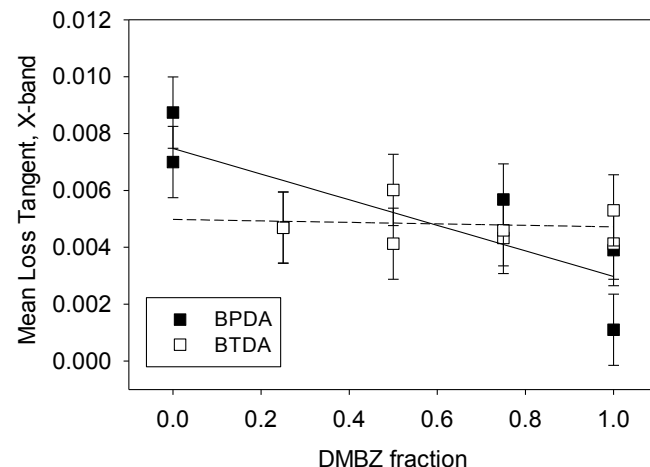
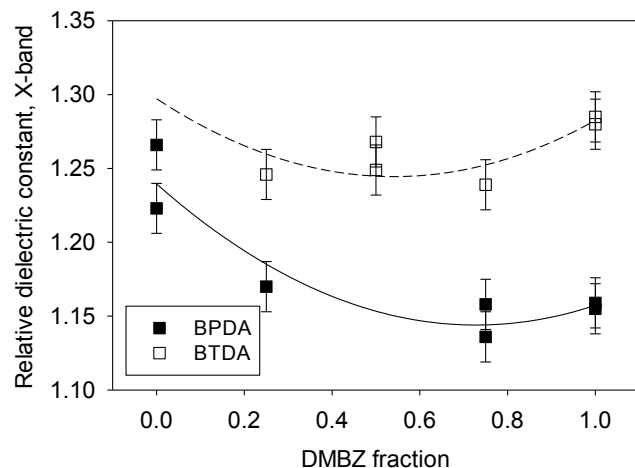
X-band

- Comprehensive number of aerogels measured at three different frequencies
- Formulations made using BTDA (dotted lines) had higher dielectric constants compared to the same formulations using BPDA (solid lines)
- Dielectric constants also decreased with increasing amount of DMBZ

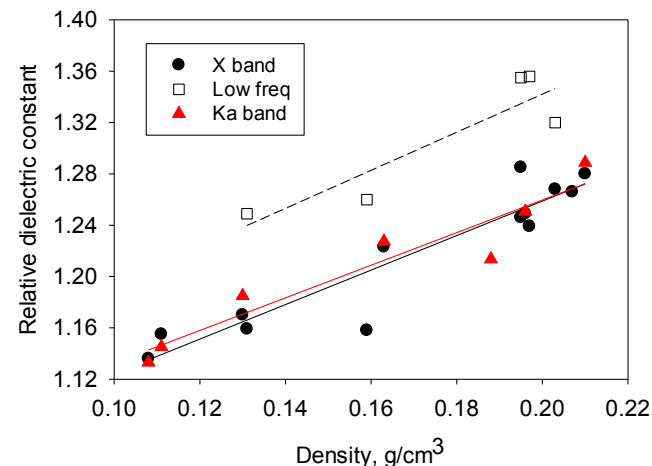


Dielectric constant, loss tangent both scale linearly with density

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- BTDA (dotted line) had higher dielectric constants compared to BPDA (solid line)
- Relative dielectric constants vary linearly with density consistent with that observed for silica aerogels
- Not possible to differentiate the effect of backbone chemistry from effect of density

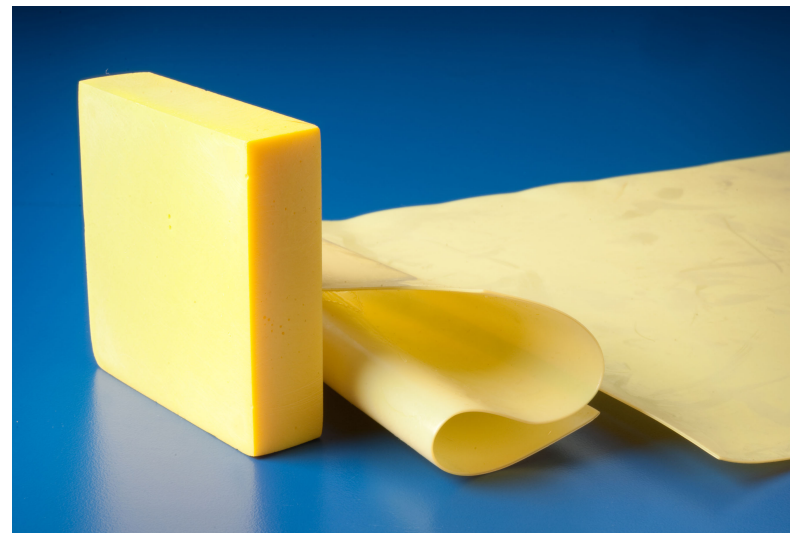
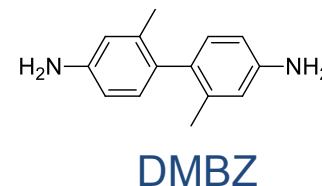
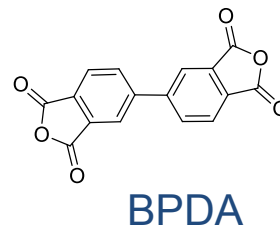




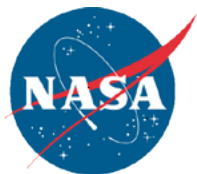
Down select for antenna fabrication

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- Formulation made using DMBZ, BPDA and TAB cross-link
 - Lowest density (0.14 g/cm^3)
 - Lowest dielectric measured (1.16)
 - Lowest loss tangent
 - Great mechanical properties
- Fabricated suitable sizes to make antennas

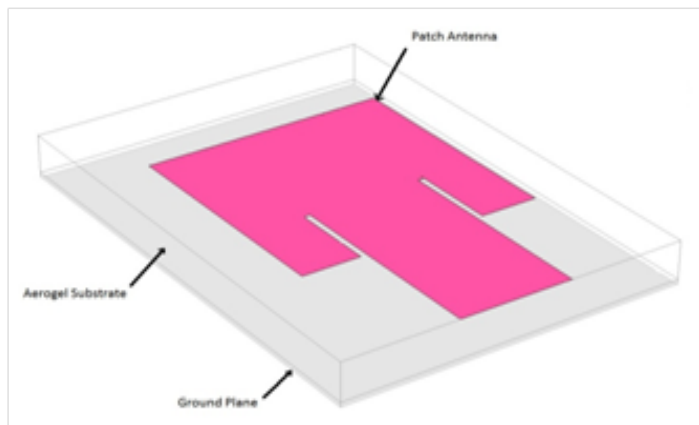


Meador, Miranda, and Van Keuls, US Patent application filed 10-16-2012



Design and fabrication of Prototype Antennas

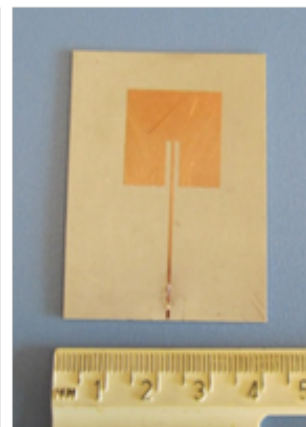
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Schematic of patch antenna



PI aerogel
($\epsilon_r=1.16$)

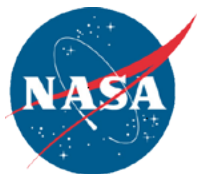


Duroid® 6010
($\epsilon_r=10.2$)



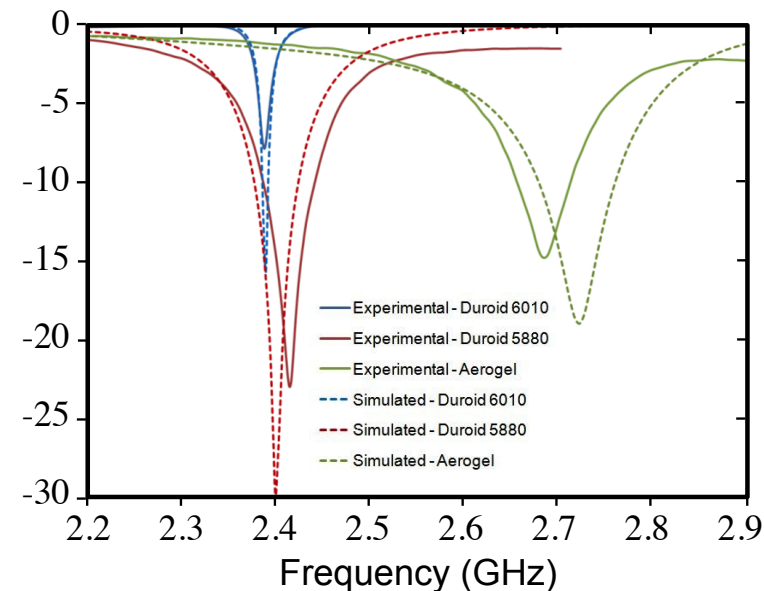
Duroid® 5880
($\epsilon_r=2.2$)

- Simulations were performed around 2.4 GHz
- Physical parameters of the antennas selected primarily based on permittivity of substrate
- The lower permittivity of the aerogel allows for a larger size of the patch thereby increasing gain

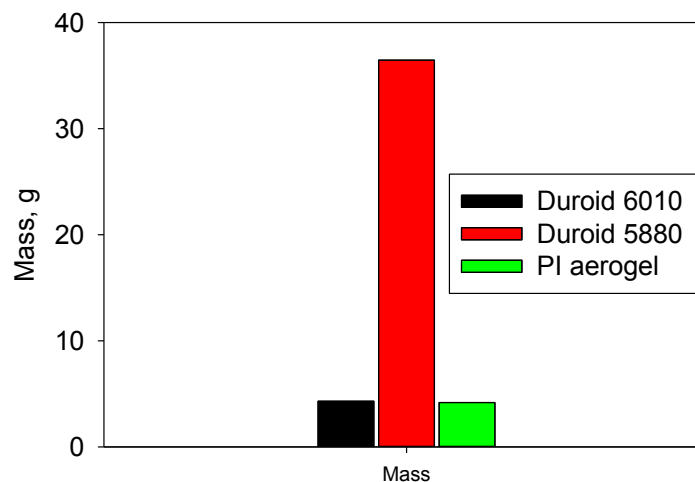
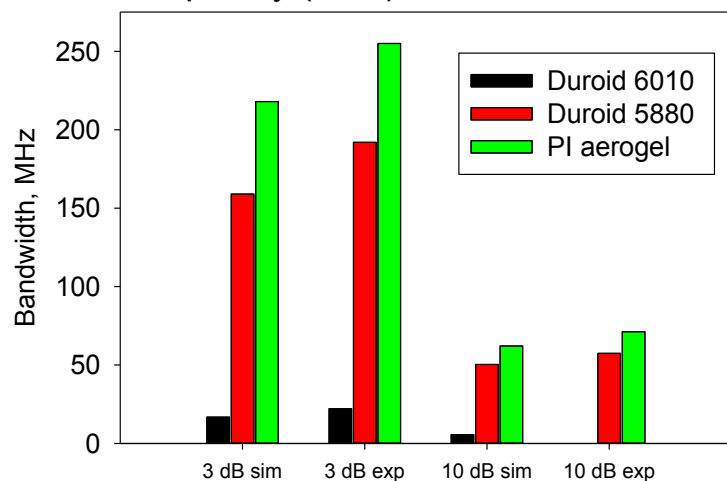


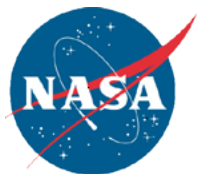
Characterization of Prototype Antennas

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- S_{11} is scattering parameter associated with reflection coefficient
- Experimental (solid line), simulated (dotted)
- Simulated and experimentally measured bandwidths at 3 dB and 10 dB are highest for aerogel antenna
- Duroid 5880 antenna which is closest to aerogel in bandwidth 10 times heavier





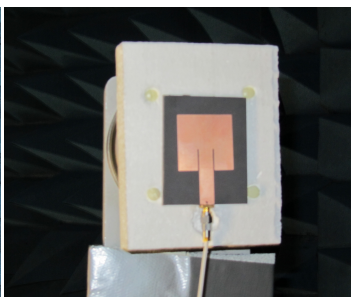
Antenna Gain Measurements

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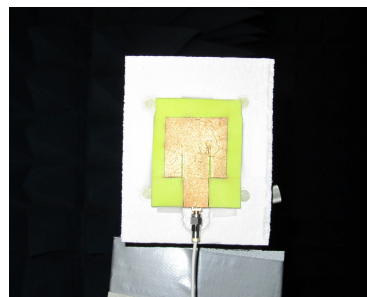
Patch antennas mounted in Far Field Antenna Range



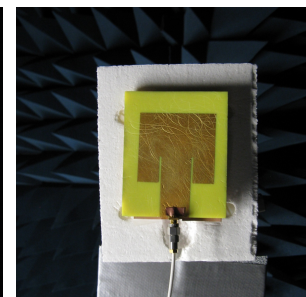
Duroid 6010



Duroid 5880

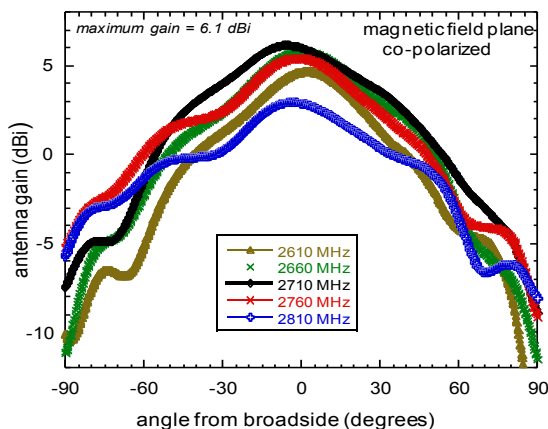


PI Aerogel 1

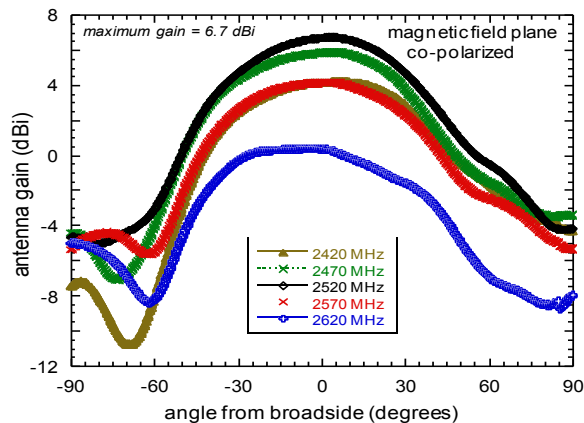


PI Aerogel 2

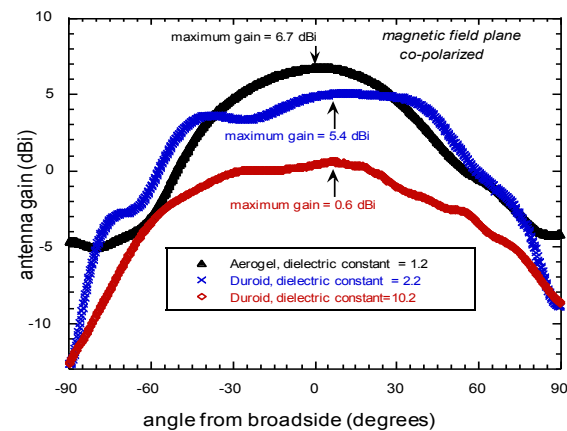
Antenna Gain vs. scan angle from broadside



PI aerogel antenna #1



PI aerogel antenna #2



Comparison PI aerogel and Duroid antennas



Summary of Phase I

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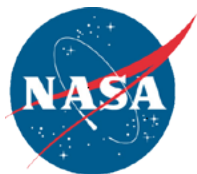
- Characterized dielectric constant and loss tangent of PI aerogels
 - PI aerogels have similar dielectric constants to those of more fragile silica aerogels
 - Similar linear relationship to density
- Fabricated simple patch antennas from down-selected PI aerogel formulation
- Benchmarked against state of practice (SOP) antenna substrates
- PI aerogels exhibited lower mass with wider bandwidth and higher gain than SOP substrates
- Increased TRL of PI aerogel antenna concept from 1 to 3
- One downside: PI aerogel not compatible with lithographic process
 - Solutions are absorbed into the pores and structure becomes distorted



Phase II approach

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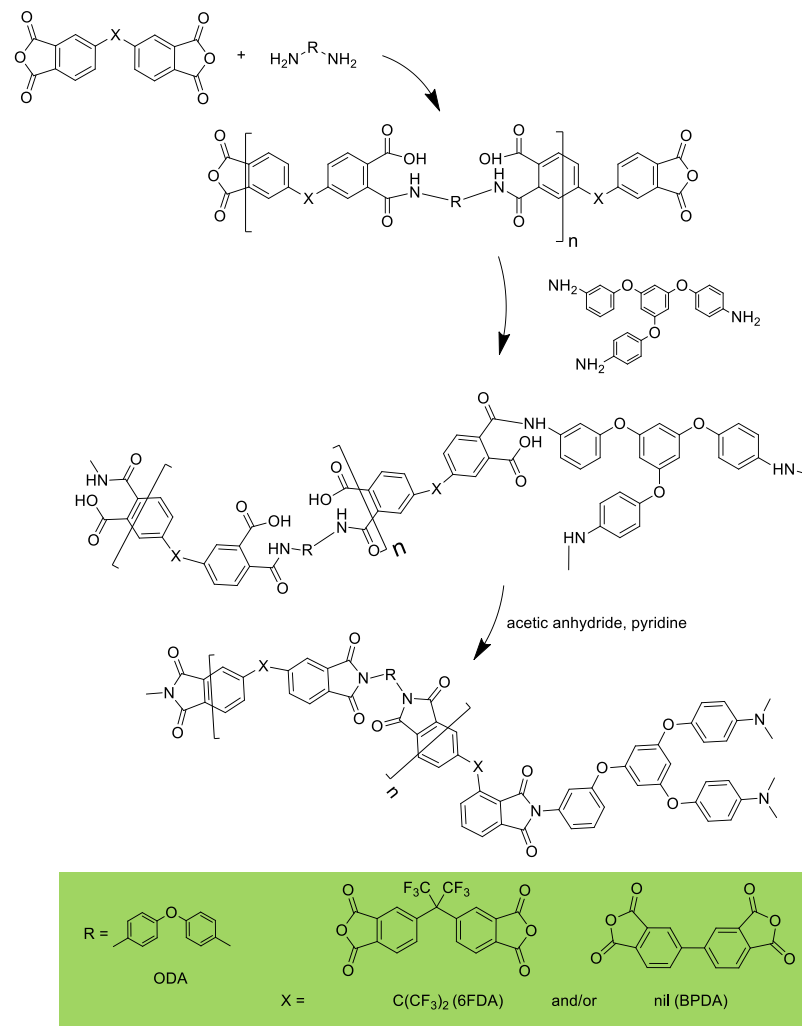
- Explore new formulations with fluorine in backbone
 - Possibly more moisture resistant, lower dielectric
 - Optimization of new PI aerogel formulations
- Refine antenna designs to take advantage of aerogel properties
- Minimize disadvantage
 - Explore new strategies for patterning (inkjet or 3D printing)
 - Explore new antenna designs
- Optimization of single element aerogel antenna feed
- Development of 1 x 2, 1 x 4 and 2 x 4 aerogel phased array antennas
- Explore the feasibility of developing aerogel based antennas in flexible aerogel substrates



Fluorinated PI aerogels

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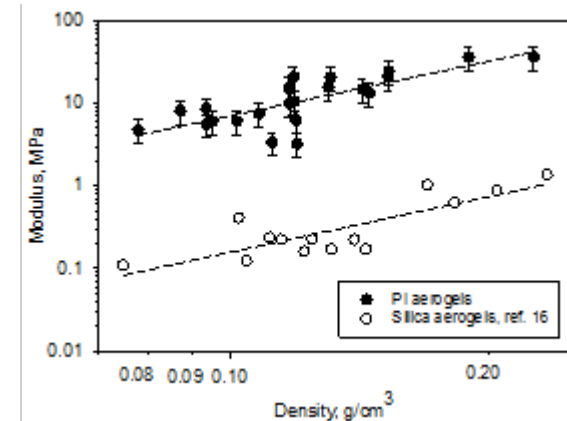
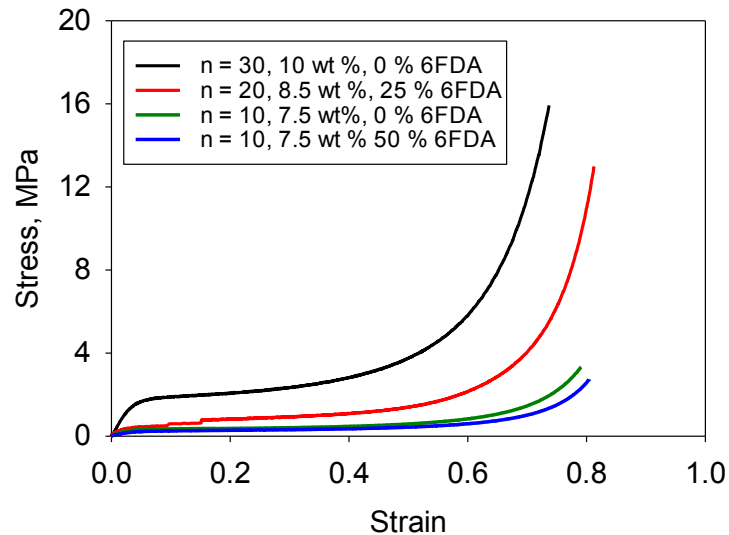
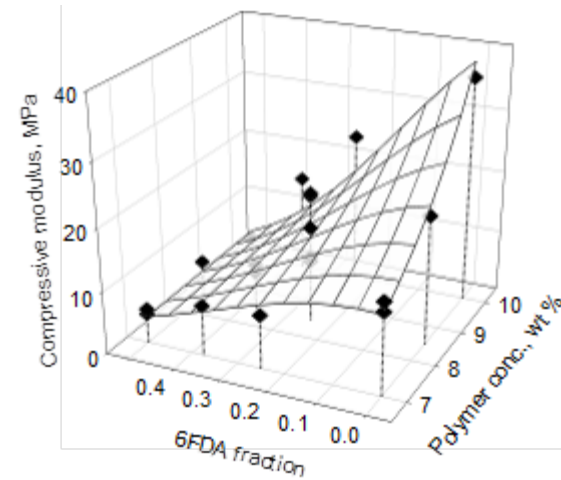
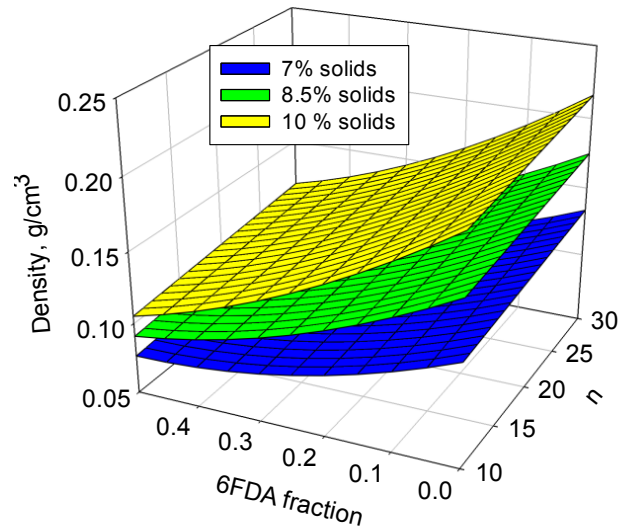
- Better moisture/solvent resistance?
- Lower dielectric properties?
- Issue
 - Fluorinated monomers less reactive
 - Combination of DMBZ with 6FDA does not gel
 - 100 % 6FDA does not gel
- Study variables:
 - Replace up to 50 % BPDA with 6FDA
 - n-value
 - Wt % solution to make gels





Results of three variable study

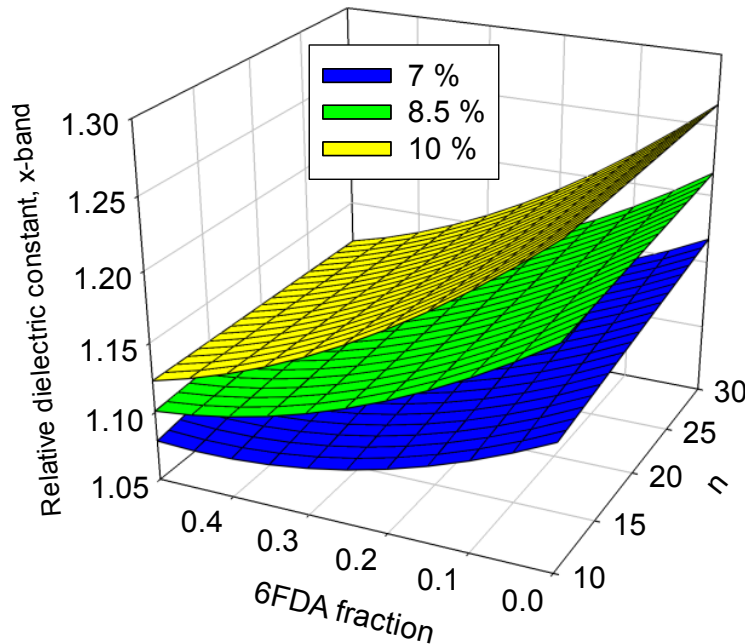
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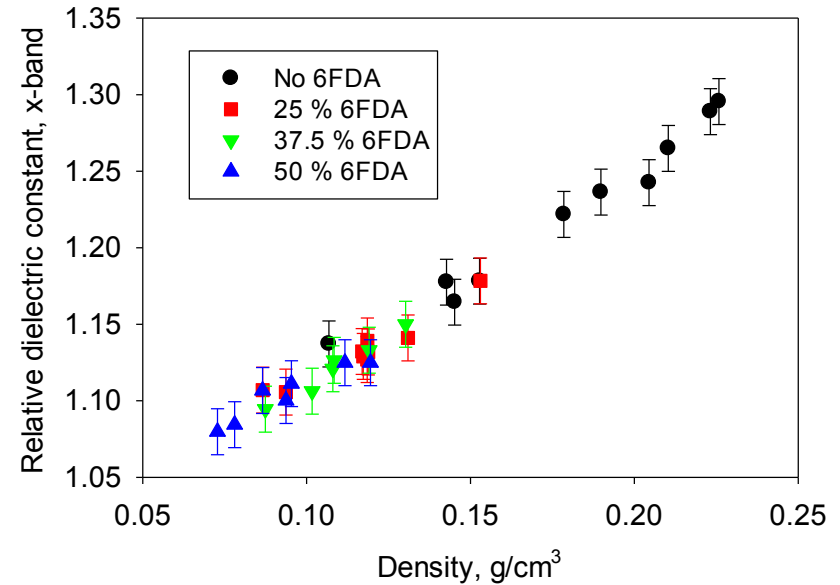


Effect of variables on relative dielectric constant

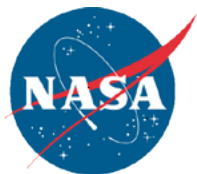
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- Same trends as density plot



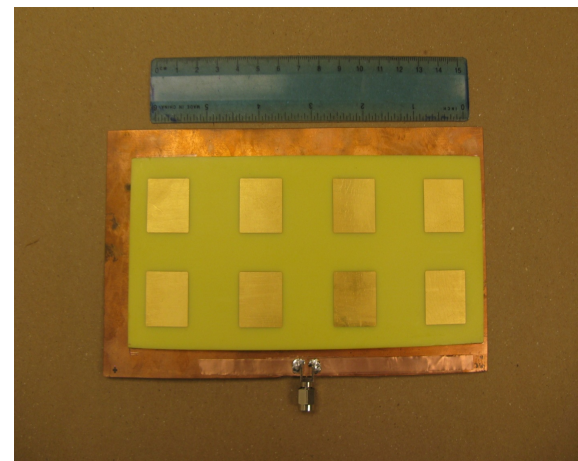
- Relative dielectric constants are completely correlated with density



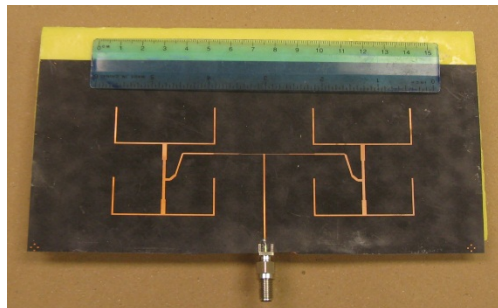
Slot-coupled 5 GHz patch antennas

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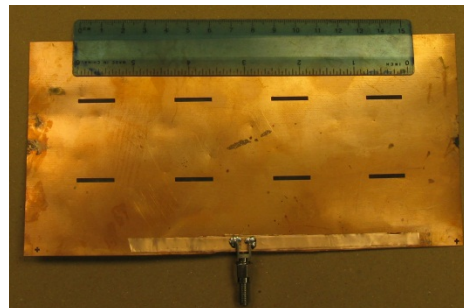
- Slot coupled design offers multiple benefits:
 - Beam-shaping elements (phase shifters, attenuators) easily inserted into feed network
 - Amplifiers (low-noise for receive, high gain for transmit) readily integrated into feed network
 - These components are essential for electronically steerable, adaptively controlled antennas
- RF energy coupled from feed network to radiating elements via aperture in ground plane
- Low dielectric of aerogel enables thicker substrate layer for high gain, high bandwidth radiating elements



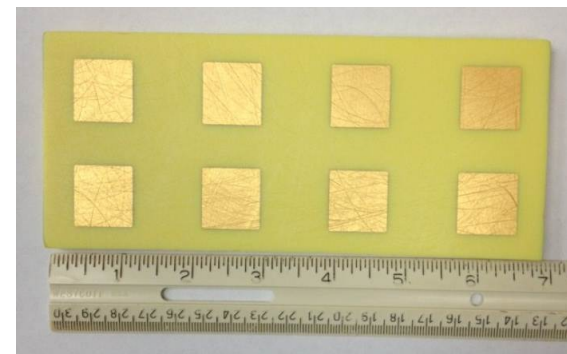
Fully assembled 4x2 array
Aperture size = 15.3 cm x 5.8 cm



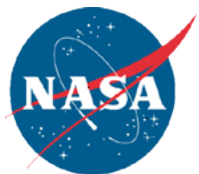
4 x 2 array feed (bottom layer)



Slotted ground plane (middle layer)



4 x 2 array on 3 mm thick PI Aerogel (top layer)



Slot-coupled 5 GHz patch antennas

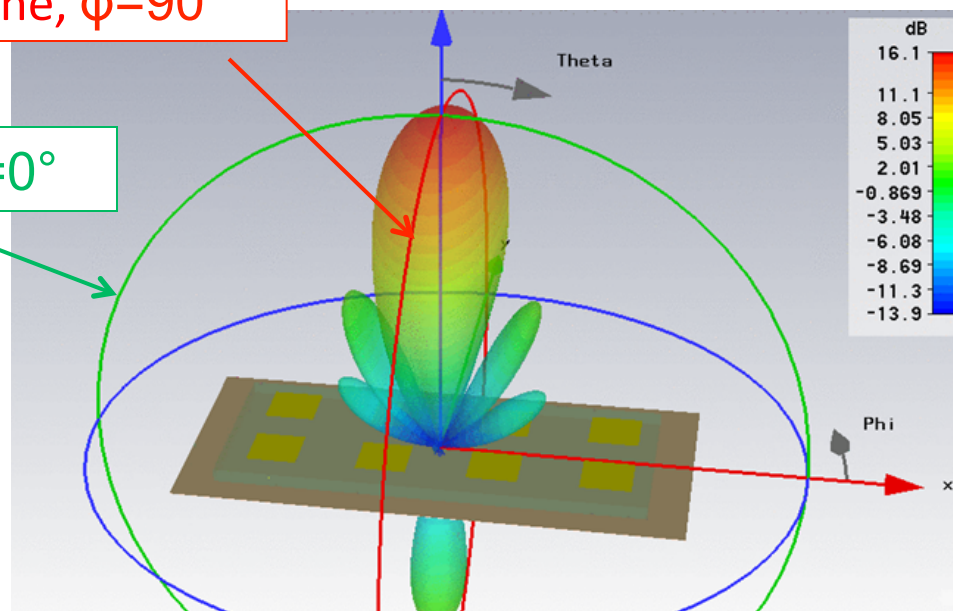
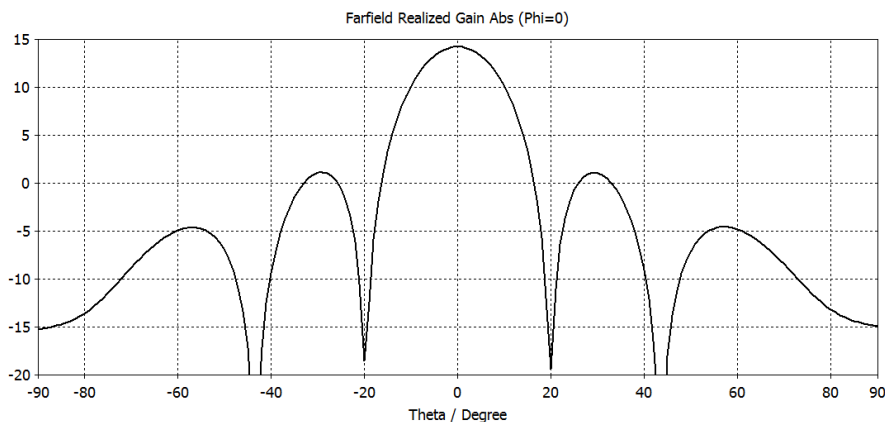
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Simulation of radiation pattern for slot coupled 4 x 2 phased array aerogel antenna

Slice, E-plane, $\phi=90^\circ$

Slice, H-plane, $\phi=0^\circ$

Two-dimensional antenna pattern along the magnetic field (H-plane) cut through $\phi=0^\circ$

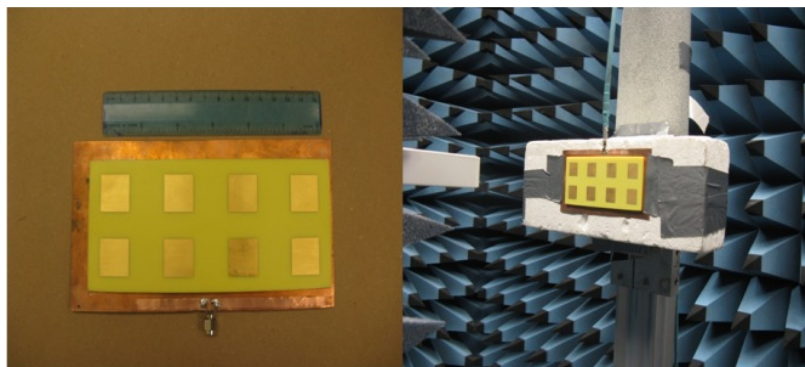


Beamwidth (3 dB)

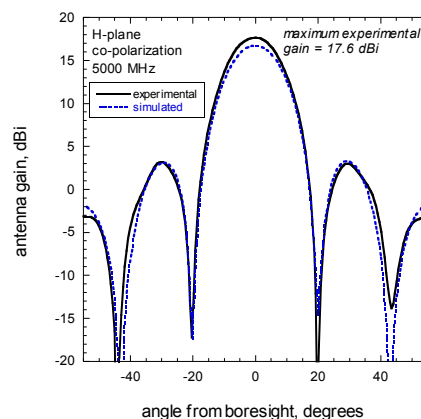


Testing of 4 x 2 array made by e-beam evaporation in GRC Cylindrical Near Field Range

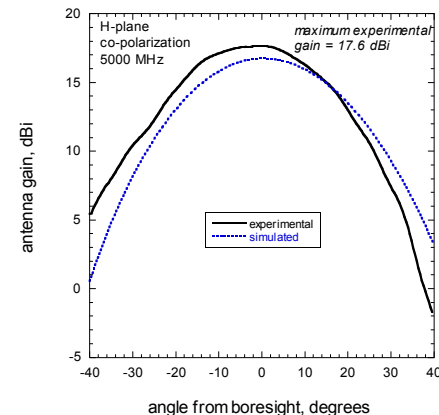
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H-plane



E-plane



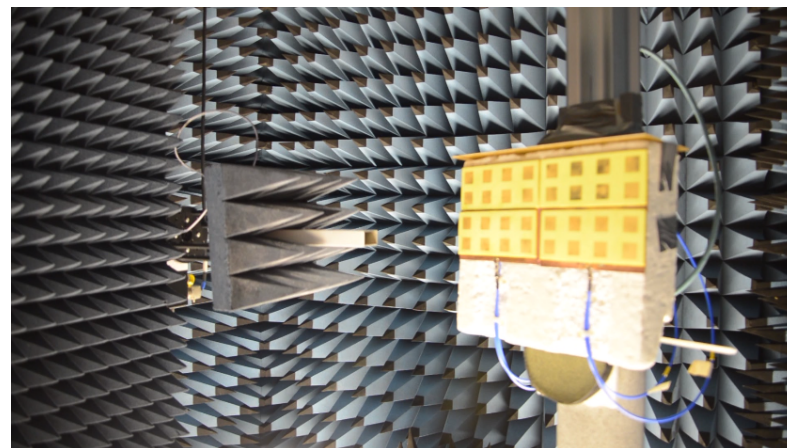
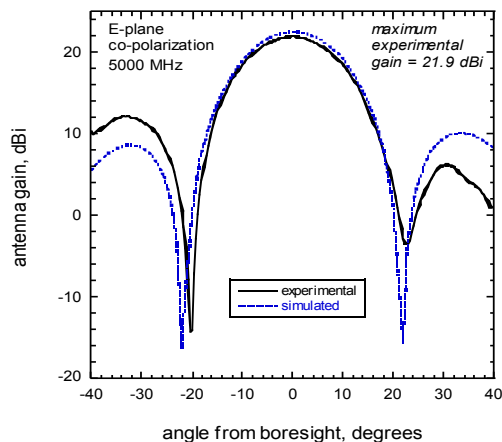
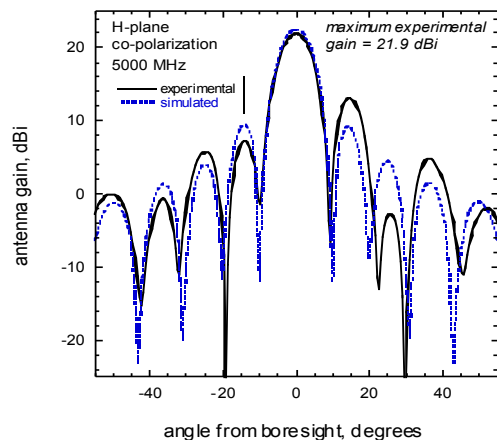
- Better performance than Duroid at <23 % of the weight
- Exhibited larger bandwidth (10 dB BW~11%, and 3dB~47% at 5 GHz)
- Higher gain (17.6 dBi), than Duroid (~6% and ~22%, and 16.3 dB, respectively)

Item	Aerogel	Duroid
Radiator tile only	5.8 g (3.68 mm thick)	88.1 g (3.18 mm)
Feed network and ground plane (i.e., 254 μ m) Duroid with copper metallization	13.9 g	14.4 g
SMA connector weight	3.9 g (male)	1.3 g (female)
Total antenna weight	23.6 g	103.8 g

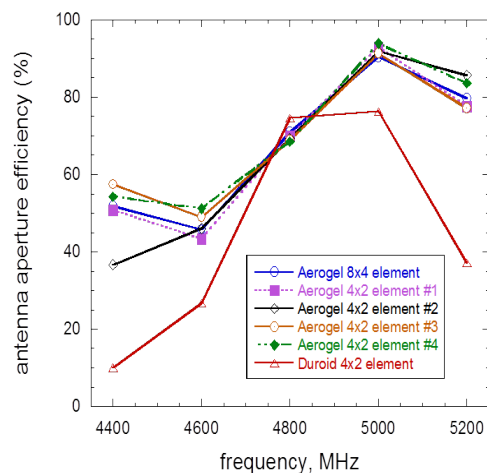
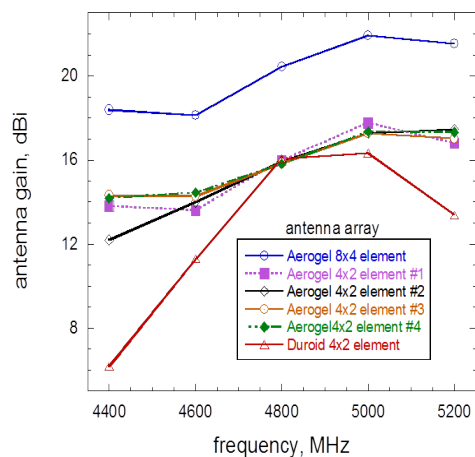


Testing of 32 element array

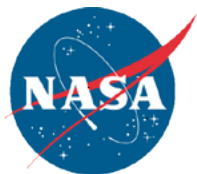
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32 element array in antenna range



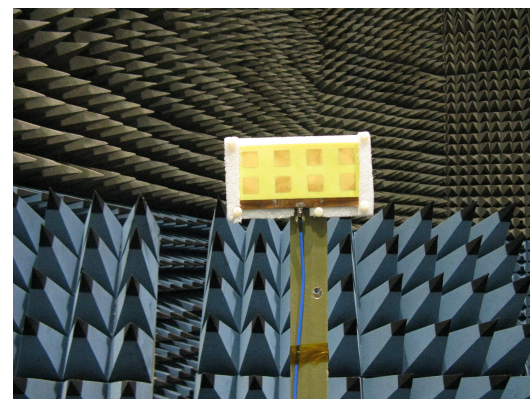
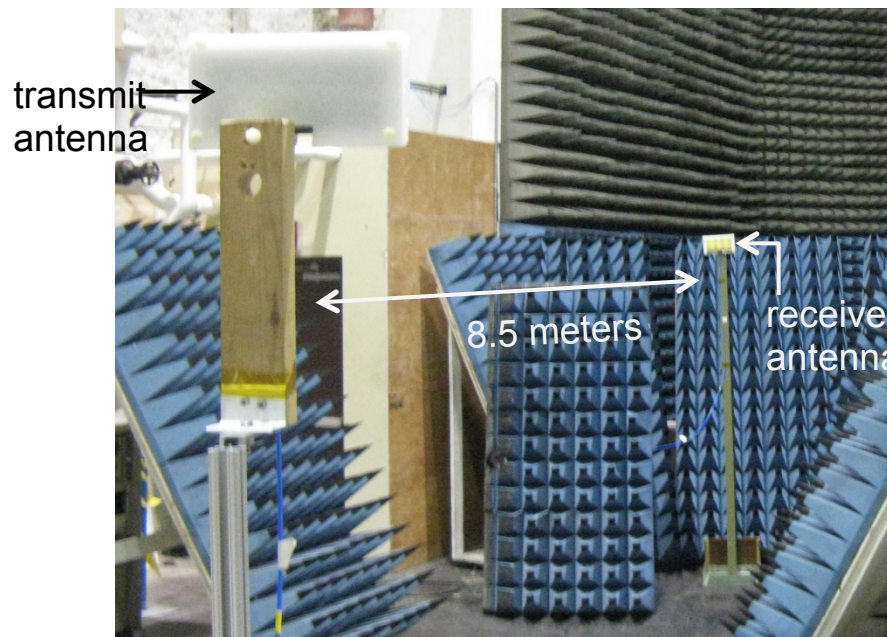
- Shows scalability of aerogel antenna performance
- Aerogel antennas surpass Duroid counterpart
 - Sustained gain over bandwidth
 - Aperture efficiency

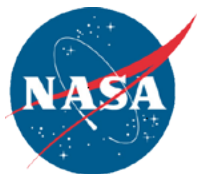


Verification of antenna performance in a terrestrial link

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- Line-of-sight experiment
 - Investigate suitability of aerogel antennas to support digital communication links with typical modulation schemes (QPSK and $\pi/4$ DQPSK)
- Error Vector Magnitude (EVM) measurement
 - Measurement of how far experimental values deviate from reference values
 - Two identical 4 x 2 aerogel arrays used as transmit (Tx) and receive (Rx) antennas
 - Separation of 8.5 m to satisfy $2D^2/\lambda$ far field criteria
 - D is the maximum antenna aperture dimension
 - λ is the wavelength corresponding to the frequency of the array
 - In our case, $D=16.1$ cm, $\lambda=6.0$ cm, and $2D^2/\lambda=0.864$ meters





Verification of antenna performance in a terrestrial link

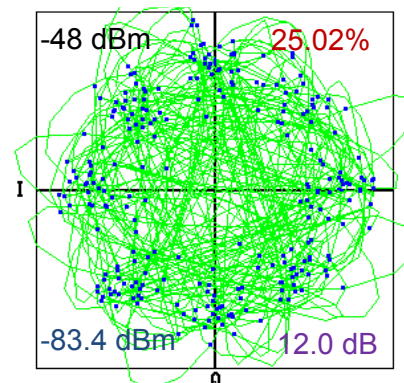
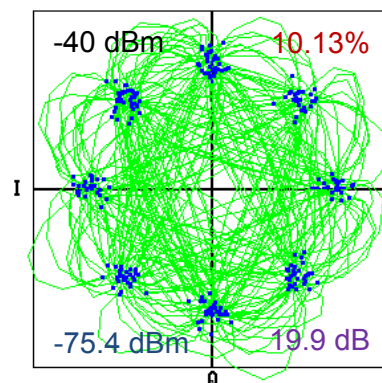
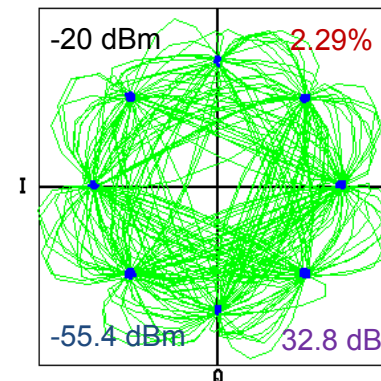
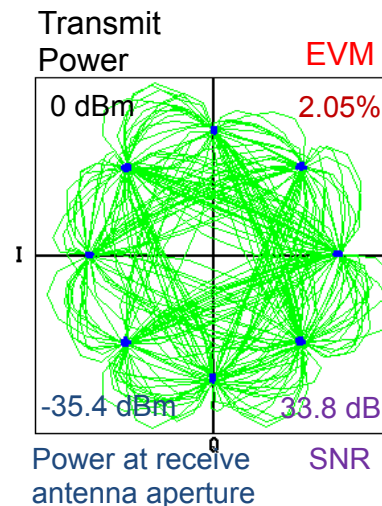
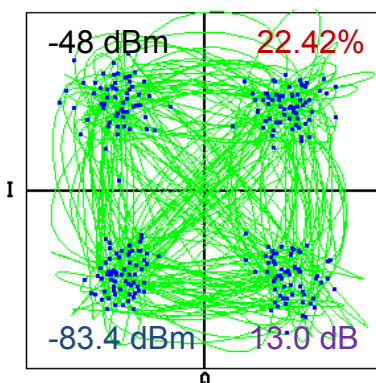
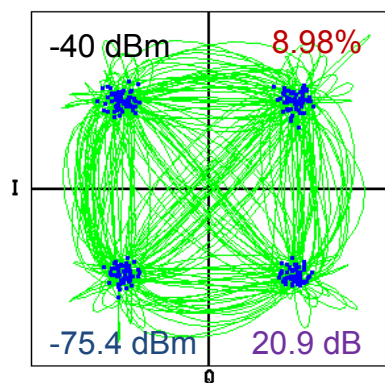
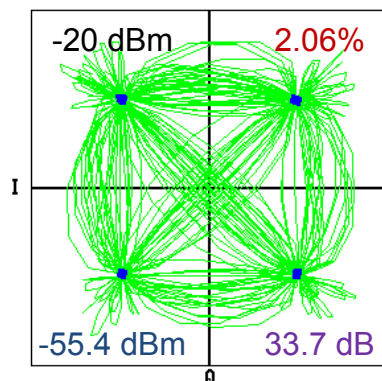
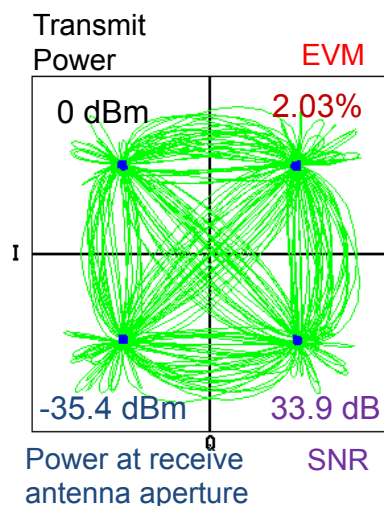
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Carrier frequency = 5.0 GHz; Symbol rate=7 Msps; data rate=14 Mbps; Avantek amplifier (AWT-6053) between Rx antenna and spectrum analyzer. Small signal gain=27 dB; Noise figure ~4

QPSK Modulation

dB

$\pi/4$ DQPSK Modulation

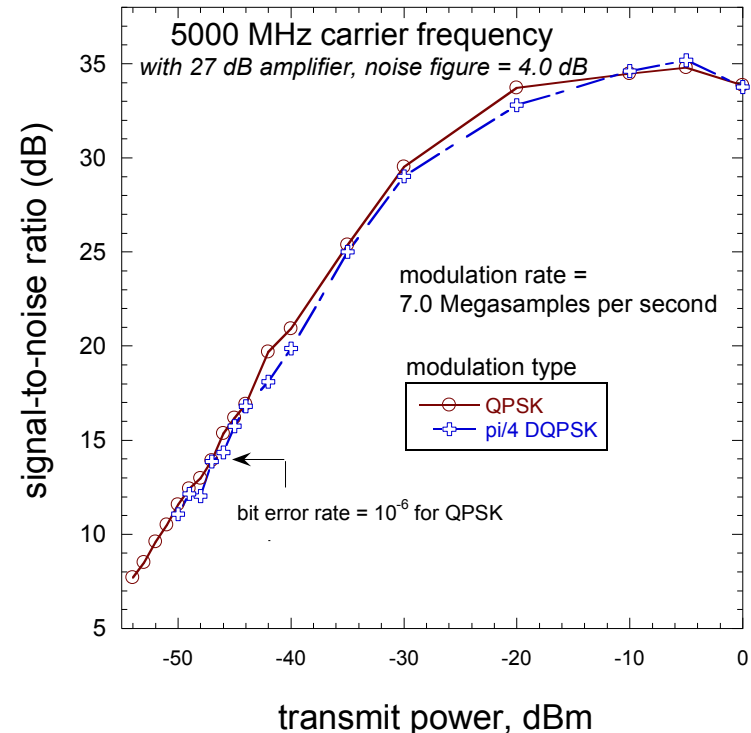
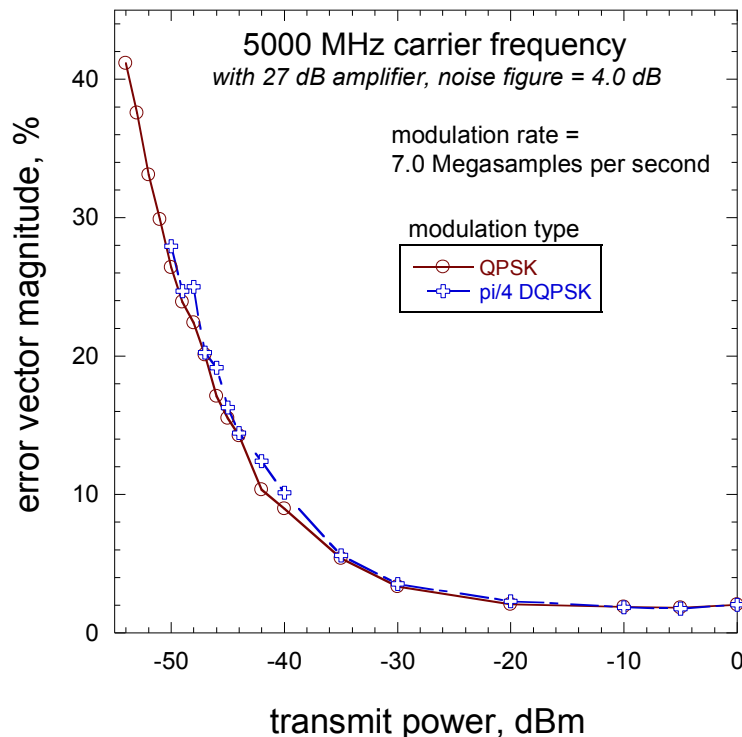




EVM provides insights into SNR and BER

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- EVM measurements provide close approximation of signal-to-noise demodulated signal, from which the bit error rate can be estimated
- Current experiment assumes channel is limited by additive white Gaussian noise

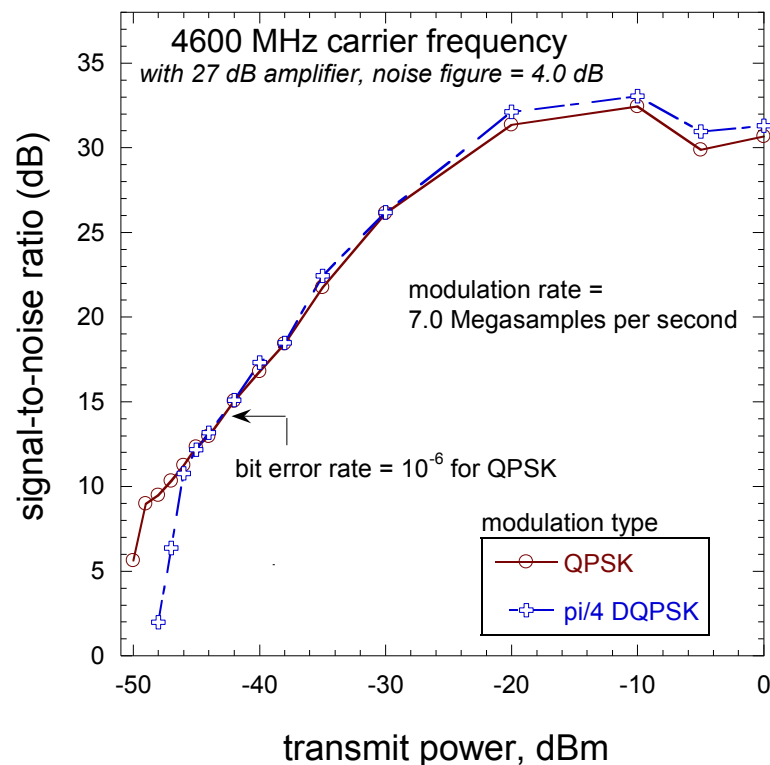
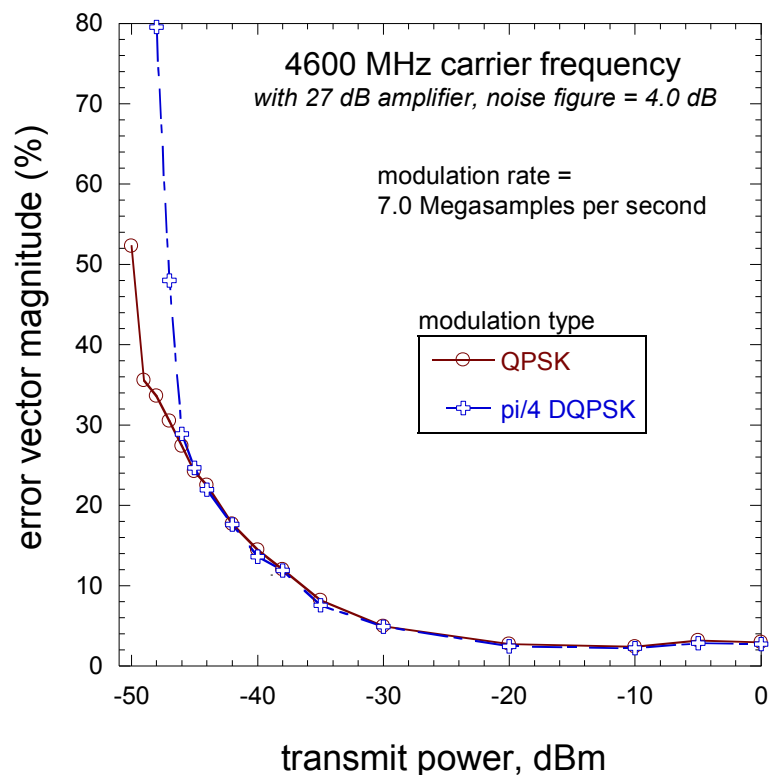


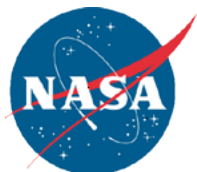


Aerogel phased array antennas operate over broad frequency ranges

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- At 4600 MHz (400 MHz removed from center frequency), antennas maintain a communications link with only ≈ 2 dB loss relative to performance at 5000 MHz
- Encouraging results not only for communications but also for radar, where the wide frequency range would be especially useful
- Similar data taken at 5400 MHz





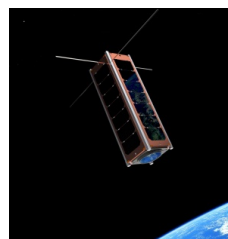
Achievable data rates with different link scenarios

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Aerogel transmit and receive antennas (2x4 element phased arrays, 15.6 dBi gain) at 5000 MHz, communications link from directly overhead to 10° from horizon



unmanned aerial
vehicle
(70,000 ft)



cubesat
(350 km)



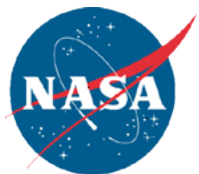
commercial
airplane
(30,000 ft)



ground terminal

- Data rates in table below are based on the following conditions:
 - Transmit power = 2 watt
 - Gain for both transmit and receive antennas = 15.6 dBi
 - Receiver noise figure = 4 dB
 - QPSK modulation
 - Free space losses based on link distance when vehicle located 10° relative to the horizon
 - Signal-to-noise ≥ 14 dB, bit error rate $\leq 10^{-6}$
 - No coding gain
 - Receiver implementation losses = 3 dB
- When vehicle is directly overhead, free space losses are reduced by 7.5 dB
 - Allowable data rates are 5.7 times higher than when the vehicle is near the horizon

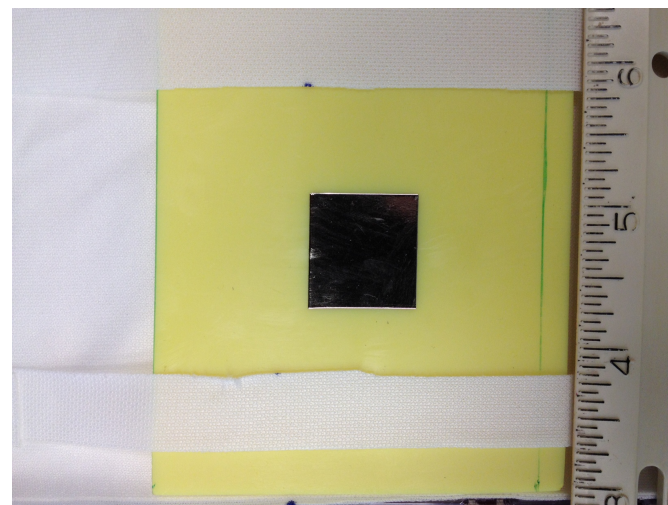
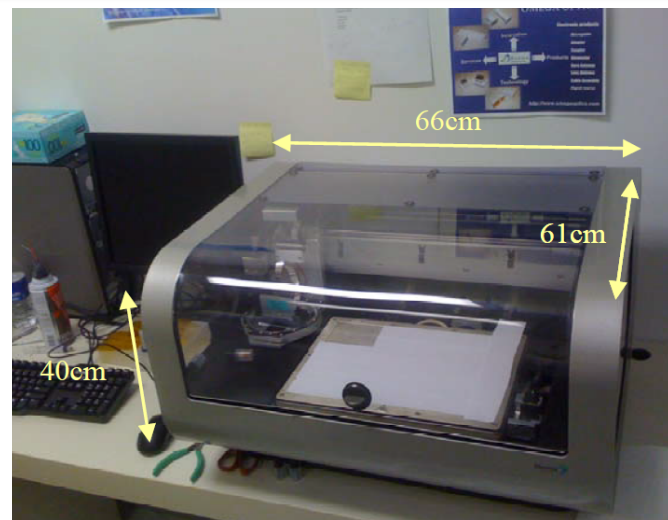
Link	Maximum link distance (km)	Data rate supported
Cubesat-to-ground	2000	38 kb/s
UAV-to-ground	120	10 Mb/s
Commercial airplane-to-ground	51	58 Mb/s

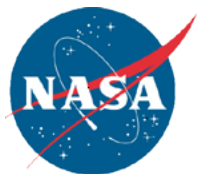


Inkjet printing of antenna patterns on PI aerogels

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- Collaboration with Professor Maggie Yihong Chen at Texas State University-San Marcos
- No cost to project
- Fujifilm Dimatix Materials Ink-Jet Printer (DMP-2800)
- Suitable to print circuits on flexible or rigid substrates
- Better than e-beam evaporation for scale-up
- Printing performed at room temperature
- Single element antenna fabricated



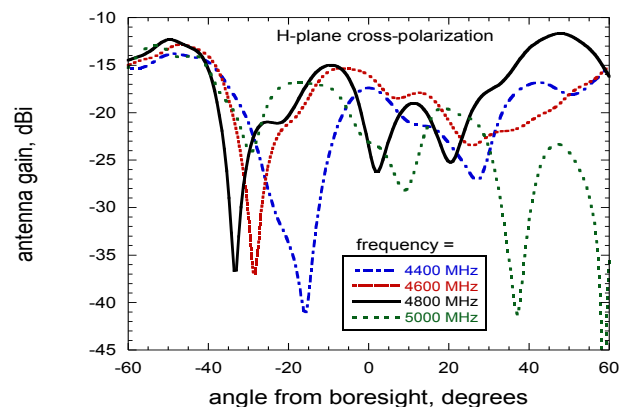
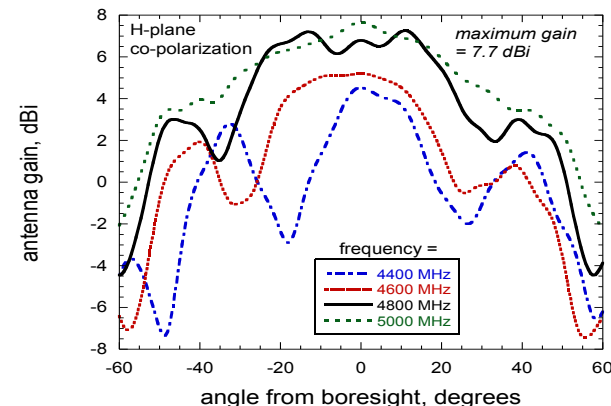


Ink-Jet Printed Aerogel Slot Coupled Antenna

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- Exhibits gain values of 4.5 dBi and 7.7 dBi at 4.4 and 5.0 GHz, respectively
- Comparable to those obtained with e-beam evaporation
- Highest antenna gains at 4800–5000 MHz, consistent with design goals
- At 5000 MHz, highest cross-polarized radiation pattern levels are at least 21 dB below highest co-polarized radiation levels

test frequency, MHz	gain (dBi)	directivity (dBi)	Efficiency (%)
4400	4.5	10.1	27.5
4600	5.2	10.6	28.9
4800	7.3	10.8	44.1
5000	7.7	10.1	56.8

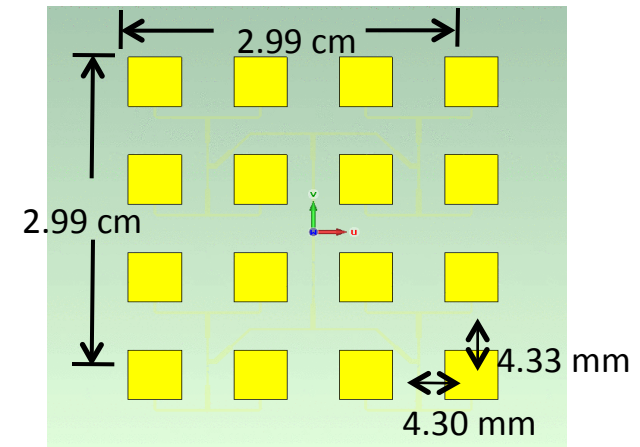




Ka-Band antennas on thin film PI aerogels

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- Aerogel thin films are flexible
 - Possibility to make conformal antennas though current design is not flexible
- 4 x 4 element aperture-couple phased array, center-feed
- Center frequency = 26.3 GHz chosen to be compatible with TDRS Ka-band return link
- Radiating elements patterned on 22 mil thick aerogel substrate
- Ideal to use ink jet printing—large acreage antennas



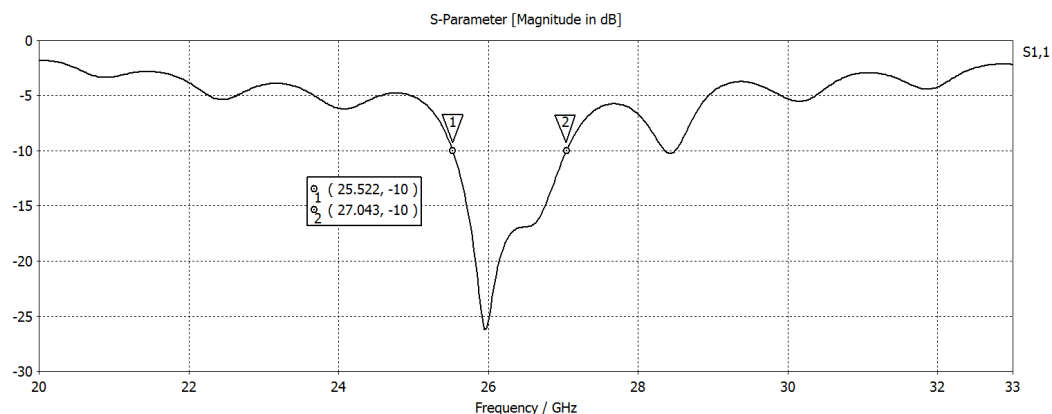
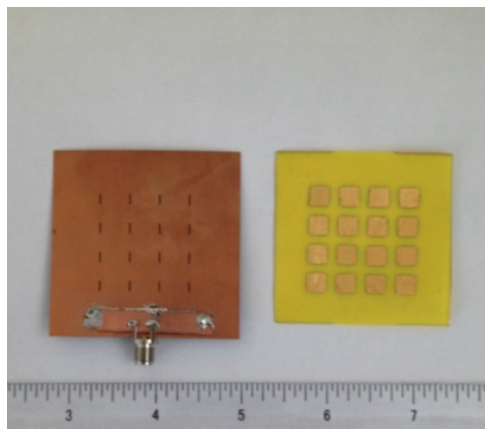
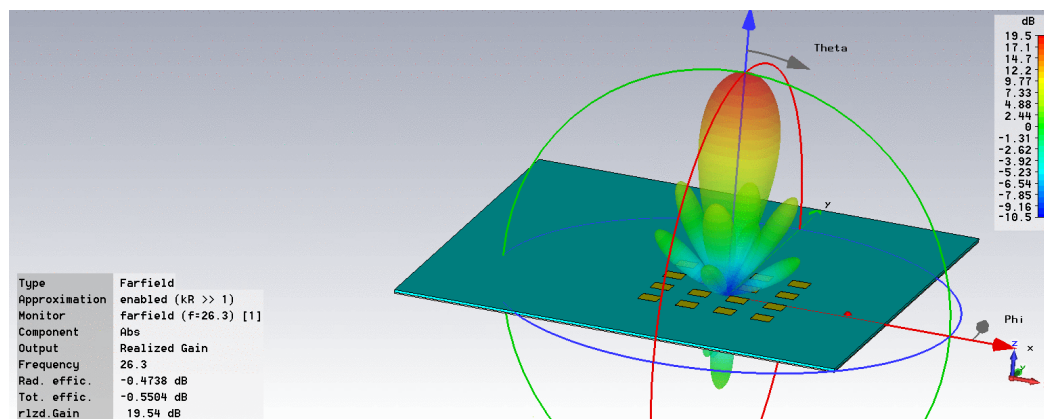
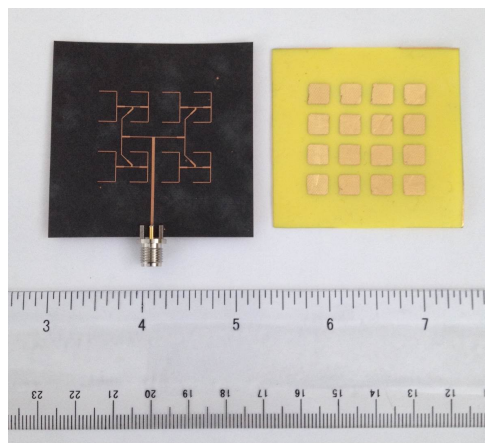
Top layer: Radiating elements patterned on top of 22 mil thick aerogel substrate

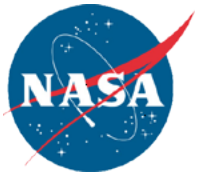


Ka-Band antennas on thin film PI aerogels

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*4x4 element aperture-couple phased array, center-feed
with 50 ohm feed line; aerogel thickness = 0.553 mm (=21.8 mils)*

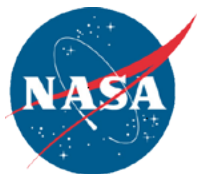




Major Findings and Conclusions

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- Optimized aerogel formulations, led to lower dielectric properties, better moisture/solvent resistance, better mechanical properties
- Demonstrated the feasibility of fabricating printed circuit antennas on optimized PI aerogel materials either by e-beam evaporation or ink-jet printed techniques
- Demonstrated performance of single-patch and phased array aerogel antennas with notable advantages in mass, bandwidth and gain over typically used microwave substrate laminate (e.g., Duroid)
- Demonstrated aerogel antennas on thick as well as thin substrates
- Demonstrated digital communications links using common modulation schemes (e.g., QPSK) that could be used to support voice, data and video communication links in UAV's, CubeSats or commercial aircraft
- Attributes of PI aerogels could be maximally exploited at S- or C-band frequencies where the large physical dimensions of the antennas offer the opportunity to tailor the array parameters (i.e., radiator size, substrate thickness, etc.) to provide optimal gain, broad bandwidth and low mass compared to typical substrates
- Higher frequencies aerogel antennas could be suitable for conformal, low profile (drag reduction applications), less complexity in design



Distribution/Dissemination

NASA Aeronautics Research Institute

Publications related to PI aerogel antennas

- Slot-Coupled Polyimide Aerogel Antennas for Aerospace Communications, F. A. Miranda, et. Al., *IEEE Trans. On Antennas and Propagation* (in preparation).
- Dielectric and other properties of polyimide aerogels containing fluorinated blocks. M. A. B. Meador, et al, *ACS Applied Materials and Interfaces*, **2014**, published on the web, January 31, 2014
- Low dielectric polyimide aerogels as a substrate for lightweight patch antennas, M. A. B. Meador, et al., *ACS Applied Materials and Interfaces*, **2012**, *4*, 6346-6353
- Tailoring properties of cross-linked polyimide aerogels, H. Guo, et al., *ACS Applied Materials and Interfaces*, **2012**, *4*, 5422–5429
- Mechanically strong and flexible polyimide aerogels cross-linked with aromatic triamine. M. A. B. Meador, et al, *ACS Applied Materials and Interfaces*, **2012**, *4*, 536–544.

Presentations and proceedings

- Aerogel Antennas Communications Study Using Error Vector Magnitude Measurements, F. A. Miranda, et al. Submitted for presentation to the *2014 IEEE International Symposium on Antennas and Propagation*, July 6-12, 2014, Memphis, TN
- Slotted Polyimide-Aerogel-Filled-Waveguide Arrays, R. Rodríguez-Solís, et al., *2013 IEEE International Symposium on Antennas and Propagation*, July 7-13, 2013, Lake Buena Vista, FL
- Low dielectric polyimide aerogels as substrates for lightweight patch antennas, M. A. B. Meador, et al., *Porous Polymers Symposium*, American Chemical Society National Meeting, New Orleans, April 2013
- Durable aerogels for aerospace and other applications. M. A. B. Meador, ACS Akron Local Section, February 19, 2014, Akron, OH
- Polyimide aerogels for aerospace applications. M. A. B. Meador, *11th Annual NanoTechnology for Defense Conference*, November 1-4, 2013, Tucson, AZ
- Fluorinated Polyimide Aerogels: Lightweight, Low-Dielectric Materials for Antenna Substrates. E. Barrios, et al, *Polymers for Aerospace and Transportation Symposium*, ACS National Meeting, September 8-12, 2013, Indianapolis, IN
- Polyimide Aerogels: Properties and Aerospace Applications. *Composites and High Performance Polymers Workshop*, ACS Division of Polymer Chemistry, July 21-24, 2013, Santa Rosa, CA

Patent applications

- Patent application: Novel Aerogel-Based Antennas for Aerospace Applications. Meador, M. A. B., Miranda, F. A., Van Keuls, F. W., filed October 16, 2012.
- Patent application: Polyimide aerogel thin films. Meador, M. A. B. and Guo, H., filed February 1, 2013.

Awards & Honors related to Seedling Research

- 2012 R&D 100 Award: Polyimide aerogels, Mary Ann Meador and Haiquan Guo
- NASA Exceptional Technology Achievement Medal 2012, Mary Ann Meador
- 2013 Nortech Innovation Award, Mary Ann Meador and Haiquan Guo



Next Steps

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Remaining work for Phase II

- Measurement of 4 x 4 Ka-band antennas on thin films PI aerogels

- EVM Measurements of 32 element array on

Beyond Seedling

- Understanding of environmental stability/need for coatings, etc.
- Trade studies (dielectric vs. mechanical properties, etc.)
- Further development of inkjet printing
- Flight demonstration (either in UAV or CubeSat)
- Need help from Aero to identify program fits
- Responding to calls for proposals where appropriate



Acknowledgments

NASA Aeronautics Research Institute

- Aerogel fabrication
 - Ms. Sarah Wright (Cal Tech intern)
 - Liz Barrios, Anna Sandberg, Emily MacMillon (USRP)
 - Dr. Baochau N. Nguyen (RXD/OAI)
- RF testing, simulations, antenna characterization
 - Dr. Fred W. Van Keuls (RHA/Vantage Partners, Inc.)
 - Dr. Carl H. Mueller (RHA/QinetiQ NA)
 - Ms. Elizabeth McQuaid (CS-FTF)
 - Mr. Nicholas Varaljay (CS-FTF)
 - Rafael Rodríguez-Solís, (University of Puerto Rico-Mayagüez)
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